Quantifying the Sequential Structure of Psychotic Behavior

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Abstract In its simplest form, a random reinforcement, choice task experiment is one in which the subject makes choices in an attempt to guess the outcome of a random number generator. The subject does not know that the pattern is random and will try to construct different strategies to increase the frequency of correct guesses. Differences in the pattern of choices are observed when clinical populations are compared against healthy controls. Additionally, the choice sequences of animals obtained before and after the administration of drugs can show marked differences. This contribution identifies mathematical methods from symbolic dynamics that can be used to provide a quantitative characterization of the sequential structure of behavior.

Introduction

In 1983 Frith and Done [1] published a seminal study of behavioral stereotypy in schizophrenia. This investigation has been the model for several subsequent studies. In a sequence of trials, subjects had to guess if a cross would appear on the left or right side of the screen. The position was assigned randomly. The subject did not know that the pattern is random and tried to construct different strategies to increase the frequency of correct guesses. In the Frith and Done study, normal controls, manic depressive subjects, patients presenting senile dementia and acute schizophrenics with positive symptoms (hallucinations, delusions, bizarre behavior) generated sequences of guesses that were "relatively random." Acute schizophrenics with negative symptoms (affective flattening, alogia, apathy, anhedonia) and chronic schizophrenics generated a high incidence of stereotyped alternating LRLR sequences. Chronic schizophrenics presenting both negative symptoms and intellectual deterioration produced repetitive sequences (LLLL….. or RRRR…..). These results were largely confirmed by Lyon, et al.[2]. A large literature examining choice behavior in clinical populations has subsequently appeared[3],[4],[5],[6],[7],[8],[9]. In most investigations, the analysis is largely limited to determining (1.) the frequency of each choice, (2.) switching percentages, (3.) the number of appearances of each of the sixteen possible tetragrams (RRRR, LLLL, RLRL,….), (4.) the appearances of each trigram and (5.) appearance of each two element pair. (As will be discussed, Paulus[5] and Magnusson[10] are a notable exceptions in this regard.) The purpose of this contribution is to identify measures from symbolic dynamics that can provide a more systematic characterization of the sequential structure of choice behavior.

Mathematical Methods

The simplest measure of a symbol sequence is its Shannon information[11]. Suppose a message (symbol sequence) is constructed from an alphabet of k symbols, and suppose that p_i is the probability of the appearance of the i-th symbol in the message. The Shannon information is

$$I = -\sum_{i=1}^{k} p_i \log_2 p_i$$

It can be shown that the maximum value of I is I=1, and that this is obtained when $p_i = 1/k$ for all i. Frith and Done[1] found differences in information between different populations, but Lyon, et al.[2] did not. Upon reflection it is seen that Shannon information will provide a very incomplete characterization of a message because it is not sequence sensitive. Consider the messages

M_1 = AAAAAAAAAABBBBBBBBBBCCCCCCCCCCDDDDDDDDDDEEEEEEEEEE

M_2 = BCBADCDAEBCDAAAEAAEEBCCDDEDACCBEDBDBAEEBEDCCABECDB

Though they are qualitatively very different, their corresponding value of information, I=1, is the same since $p_1 = p_2 = \cdots\cdots = p_5 = .2$ in both cases. Alternative measures are sensitive to sequential structure.

Previous analyses of choice behaviors have looked for different substrings (words) in the behavior sequence. This can be made more rigorous by calculating the topological entropy of a message[12]. Again suppose a message is constructed from an alphabet of k symbols. With an alphabet of k symbols, the maximum number of possible words of length n is k^n. By definition, all possible words appear in a random message. In a non-random message the number of observed words of length n grows with n, but not as rapidly as it does for a random message. Let N(n) be the number of words of length n actually observed in the message. N(n) grows exponentially at the rate $H_T n$ where H_T, the topological entropy is between zero and one.

$$N(n) \;\alpha\; k^{H_T n} \le k^n$$

If $\log_k N(n)$ is plotted as a function of n, it will have slope H_T. Strictly, H_T is defined in the limit of infinitely long messages

$$H_T = \lim_{n\to\infty} \frac{\log_k N(n)}{n}$$

If the message is random, then $N(n) = k^n$ and $H_T = 1$. Suppose the message is constructed by repeating a single symbol (M=LLLLL…..). In that case, N(n)=1 and $H_T = 0$. Intermediate values of H_T can be generated by chaotic sequences.

The topological entropy is sensitive to the appearance of each substring of length n, but it is insensitive to the frequency of each appearance. In contrast, the metric entropy incorporates a dependence on the relative frequency of each substring[13]. Let S_n denote a substring of length n. Let $F(S_n)$ denote the number of times that it appears. The probability of S_n is $P(S_n)$.

$$P(S_n) = F(S_n) / \sum_{\text{all } S_n} F(S_n)$$

I_n is the information obtained from observing substrings of length n.

$$I_n = -\sum_{\text{all } S_n} P(S_n) \log P(S_n)$$

The information content of a substring increases with its length.

$$I_n \ \alpha \ H_M n$$

If I_n is plotted as a function of n, it should have a slope H_M, which is the metric entropy. As in the case of topological entropy, metric entropy is defined mathematically as a limiting case.

$$H_M = \lim_{n\to\infty} I_n / n = \lim_{n\to\infty} \left\{ \frac{-\sum_{\text{all } S_n} P(S_n) \log_2 P(S_n)}{n} \right\}$$

If the message is composed from an alphabet of k symbols, there are k^n possible substrings of length n. In the case of a random sequence, each substring appears with equal probability, $P(S_n) = 1/k^n$. For the case of a random sequence, the sum contains k^n identical terms.

$$H_M = \lim_{n\to\infty}\left\{\frac{-\sum_{\text{all } S_n}\frac{1}{k^n}\log_2\frac{1}{k^n}}{n}\right\} = \log_2 k$$

If the message is constructed by repeating a single symbol, there is only one substring of length n in the message, and the probability of its appearance is one. No information is obtained by observing a process that has a certain outcome. $I_n = 0$ and hence $H_M = 0$.

Several other methods for characterizing order in symbol sequences should be noted briefly. Frith and Done[1] reported that for healthy controls and several patient groups the choice pattern was "relatively random." The Lempel-Ziv complexity[14] is an important method for characterizing the degree of randomness in a symbol sequence. A normalization of Lempel-Ziv complexity that reduces its sensitivity to the length of the message has been constructed[15],[16]. We have published elsewhere a detailed didactic presentation of this measure along with pseudocode for its calculation[17]. The topological entropy, metric entropy and Lempel-Ziv complexity give low values for regular sequences and high values for random sequences. A number of investigators have published definitions of complexity that give low values for both regular and random processes and higher values for irregular deterministic chaotic processes[18],[19],[20],[21]. In a series of publications, Paulus and his colleagues have used sequence sensitive methods to characterize choice behavior in schizophrenia patients[4],[5],[6],22. The fluctuation spectrum of local substring entropies was calculated. They observed that "schizophrenic patients exhibited significantly less consistency in their response selection and ordering, characterized by a greater contribution of both highly perseverative and highly unpredictable subsequences or responses within a test session[4]."

What symbolic dynamics doesn't measure

An analysis of choice behavior with methods from symbolic dynamics proceeds without reference to whether or not a guess was correct. Measures that, for example, determine the frequency of implementation of a win-stay strategy are not generated by an examination of the response sequence alone. The frequency of a win-stay strategy can be informative. Its frequency is reduced in schizophrenic subjects[2]. The latencies (time required to respond) are not incorporated into an analysis based on symbolic dynamics. Magnusson[10] has constructed a measure that is sensitive to both choice sequence and latency. It has been applied to data obtained from schizophrenics by Lyon and Kemp[23]. Using this measure they found that schizophrenic and manic patients showed more complex patterns than controls. The complexity of the response structure was reduced by clozapine. It should be noted that it is not necessary to chose between measures. Several measures can be incorporated into a multivariate discrimination. The coefficient of determination can be used to determine which measures are most effective in discriminating between different groups of subjects.

Discussion

The analysis of choice task behavior is not limited to studies of schizophrenia. Studies of perseverative behavior have been conducted with autistic patients[24] and with traumatic brain injury patients[25]. The experimental paradigm of choice and random reinforcement has a long history in animal studies[26]. Animal experiments are important in providing a bridge between human clinical studies and investigations of animal models of schizophrenia[27]. For example, Evenden and Robbins[28],[29] observed psychotic choice behaviors in rats treated with amphetamine. Similarly, stereotyped behavior has been seen in human control subjects following administration of amphetamine[30]. It is suggested that analysis of behavioral sequences with methods from symbolic dynamics will provide a more finely grained quantitative characterization of behavior. Further studies may show that it is possible to use dynamical measures of human choice performance longitudinally to assess the response to treatment.

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